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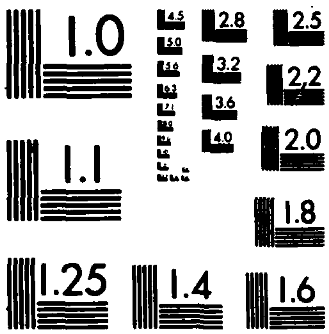
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TRANSBEAM — NSWC'S TRANSFORMER-DRIVEN ACCELERATOR

BY J. R. SMITH V. L. KENYON, III D. TONDO D. C. SWIGER H. S. UHM

RESEARCH AND TECHNOLOGY DEPARTMENT

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In this report a description of the transformer driven accelerator in operation at NSWC is presented. This accelerator, named Transbeam, uses a high-voltage step-up transformer for voltage multiplication, and a water-filled coaxial transmission line for pulse compression. For typical operating conditions the nominal output pulse has a 700 kV amplitude and a 100 ns duration. The accelerator's output impedance is 7 ohms. Theory of operation, engineering details, and characteristic results are discussed.

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FOREWORD

In this report a description of the transformer-driven accelerator in operation at the Naval Surface Weapons Center (NSWC) is presented. This accelerator, named Transbeam, uses a high-voltage step-up transformer for voltage multiplication, and a water-filled coaxial transmission line for pulse compression. For typical operating conditions the nominal output pulse has a 700 kV amplitude and a 100 ns duration. The accelerator's output impedance is 7 ohms. Theory of operation, engineering details, and characteristic results are discussed. We gratefully acknowledge assistance provided by Professor M. J. Rhee of the University of Maryland. This work was supported by the Independent Research Fund at NSWC.

Approved by:

CARL W. LARSON, Head
Radiation Division

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CHAPTER 1

INTRODUCTION

The construction of the Transbeam accelerator at NSWC was undertaken in order to produce a relatively compact, high-voltage, high-current accelerator. To this end a high-voltage air-core pulse transformer was used for voltage multiplication. The majority of other accelerators with similar pulse specifications use Marx generators instead. However, transformers have some advantages over the Marx generators which are generally used in accelerators, such as: (1) they allow for a more compact design since an oil filled Marx tank is not necessary, and (2) they allow one to greatly reduce the number of spark gaps and consequently require less maintenance. Two disadvantages are: (1) transformers suitable for use in accelerators have not been designed for voltages above a few megavolts, and (2) charging times of pulse forming lines (PFL's) are longer with a transformer than with a Marx and, therefore, put more stressing requirements on PFL design. The high-voltage transformer used in Transbeam was patterned after a design of Rohwein[1] at Sandia. Other accelerators which have used a transformer charged PFL are a 300 kV machine at Sandia,[2] a 700 kV accelerator at the University of Maryland,[3,4] and a 1 MV accelerator at McDonald Douglas Research Laboratory.

CHAPTER 2

ACCELERATOR DESCRIPTION

Figure 1 is a schematic of the accelerator which shows three major elements, (1) a high-voltage generator, (2) a pulse forming line, and (3) a vacuum diode. In the following paragraphs a detailed description of each element is given along with a brief discussion of its operation. A summary of Transbeam specifications are listed in Table 1.

1. The high-voltage generator consists of a capacitive energy storage system and a high-voltage transformer. Figure 2 gives details of the high-voltage generator electrical connections. Six capacitors (4 μF, 5.1 kJ, 20 nH) are used for the primary energy storage. The capacitors are configured in two banks, with three parallel capacitors in each bank. The capacitors are contained in an insulating box, and the capacitor casing of each bank is not grounded but is connected to the transformer's single primary turn through feed plates. The primary turn is fabricated as two semicircular pieces which are bolted together at the top of the transformer. The bolted connection is grounded through the outer conductor of the pulse forming line. The center stud terminals of each bank are connected to an gas-filled (air @ 40 psig) rail-gap switch which is positioned between the two banks. The transformer's secondary consists of 41 turns wrapped in a spiral arrangement as shown in Figure 2. One end of the secondary is attached at the grounded juncture at the transformer's top, and the other end is attached to a rod positioned at the transformer's center. Each turn is insulated by 11 mylar films (5 mil) and 1 paper sheet (0.5 mil). The transformer windings are immersed in oil for insulation.

Pulsing of the transformer occurs as follows. The capacitor banks are charged with a high-voltage dc power supply on a timescale of approximately 1 minute. One bank is charged negatively (-V) and the other positively (+V). The rail-gap switch is closed, either by command from a high voltage mini-Marx trigger circuit, or by rapid expulsion of air from the gap via a solonoidal operated gas valve. Closure of the rail-gap switch effectively connects the two capacitor banks in series, therefore the voltage applied to the transformer's primary turn is twice the capacitor bank charging voltage (2V).

2. The pulse-forming line uses a coaxial conductor geometry and a water dielectric. Nominal PFL dimensions are: 60 cm outer conductor diameter, 22 cm inner conductor diameter, 1.5 m conductor length. The water is continuously flowed through the PFL and through a deionizer bottle to achieve a resistivity of about 15 Mohm-cm. A spark gap switch pressurized with SF_6 gas is used to discharge the PFL into the load. This output switch is encased in an insulating housing and has hemispherical electrodes fabricated from a copper-tungsten alloy.

Resonant charging of the PFL by the high-voltage transformer (i.e., the resonant frequency of the transformer primary circuit is matched to the resonant frequency of the transformer secondary circuit, $L_pC_p = L_sC_s$) allows maximum energy transfer efficiency. In order to achieve this matching condition, a tuning inductor is inserted in the transformer secondary circuit. It is encased in a short oil-filled section which serves to connect the high-voltage generator to the PFL and is connected as shown in Figure 1. Single resonance charging, where the maximum PFL voltage is attained on the peak of the first half cycle, requires a transformer-circuit coefficient of coupling near unity which is difficult to achieve in a high-voltage, high-gain transformer. Dual resonance charging, where the maximum PFL voltage is attained on the peak of the second half cycle, requires a coupling coefficient of 0.6,[5] which is more easily obtained in transformer construction. This is the method of charging used on Transbeam. PFL charging is monitored with a capacitive voltage probe which is located as shown in Figure 1. A representative trace is shown which reveals that the total charging time of the PFL is about 6 μs. In this example the PFL is charged positively on the first half cycle, and negatively on the second half cycle at which time it was discharged into a load. This is the mode of charging used for electron acceleration.

The PFL is discharged as follows. Gas pressure is adjusted in the output switch so that it will undergo self breakdown when the maximum voltage (i.e., the peak voltage of the second half cycle) is applied to the PFL. Switch breakdown is monitored by the PFL's capacitive voltage probe and is indicated as the location where the voltage drops abruptly to zero. At switch breakdown the PFL discharges, resulting in a PFL output pulse which is compressed in time with respect to the transformer's output pulse. This process may be analyzed by transmission line analysis.[6] If a matched load is assumed, a single square pulse results, with a pulse amplitude one half of the PFL charging voltage. Unmatched loads result in pulse reflections. Pulse length is determined by the two-way transit time of an electromagnetic wave in the dielectric-filled PFL. The speed of such a wave is given by

$$v = c/(K_m K)^{1/2} \qquad (1)$$

where c is the speed of light in vacuum, K_m is the relative permeability of the dielectric, and K is the dielectric constant. For the water dielectric used here, the speed is 3.4 cm/ns. Since our PFL length is 1.5 m, the two way transit time is approximately 90 ns. In order to determine the value required for a matched load, the PFL's impedance may be calculated as follows. For a coaxial transmission line the capacitance and inductance may be given as

$$C = \frac{2\pi K \varepsilon_0 \ell}{\ln(r_2/r_1)}, \qquad L = \left\{\frac{K_m \mu_0 \ell}{2\pi}\right\} \ln(r_2/r_1), \quad \text{mks units} \qquad (2)$$

where ℓ is the PFL length, r_2 is the outer conductor radius, r_1 is the inner conductor radius, ε_0 is the permittivity of free space, and μ_0 is the permeability of free space. The PFL impedance is calculated according to $Z = (L/C)^{1/2}$ and is 7 ohms.

Typical voltage and current waveforms characterizing PFL output are shown in Figure 1. The voltage is measured with a capacitive probe located in the short length of water section which connects the PFL and diode. The voltage across the diode gap equals the voltage measured by this probe plus an L di/dt term, where L is the diode inductance. However, the inductance term which is a factor mainly during the rise and fall times of the pulse is often ignored, and the voltage measured by this probe is also referred to as the diode voltage. Current is measured with a single turn magnetic pick-up loop located in the diode. The pick-up loop signal is integrated passively with an RC circuit. For the particular data shown in Figure 1, the capacitor bank charging voltage was ±25 kV. Therefore the voltage applied across the transformer primary was 50 kV; and the PFL output was 600 kV (plateau value). The peak current was approximately 50 kA. The diode impedance for this particular shot was 12 ohms. This is higher than our matched load impedance and, as a result, some small amplitude reflections are evident in the waveforms.

3. The diode region contains the high-voltage gap used for particle acceleration. A critical region in the diode is the insulator which separates the inner conductor (which is at high voltage) from the outer conductor (which is grounded). In order to prevent breakdown across the insulator's surface the diode is maintained at high vacuum (1×10^{-5} Torr) with an oil diffusion pump. The high vacuum is also required for efficient acceleration of particles in the high-voltage gap. An ion gauge tube is installed in the diode chamber for vacuum measurement. Details of the electrodes used in the diode depend on the desired diode impedance and the type of charged particles to be accelerated. Electrodes used for electron acceleration and ion acceleration are described in the next chapters.

Transbeam's mechanical design was greatly influenced by an effort to make accelerator maintenance and repair as painless as possible. To this end V-band couplings were used at several interfaces in the accelerator such as the diode chamber to PFL interface and the PFL to tuning inductor section interface. This type of coupling can be removed easily in order to separate the accelerator into sections. The entire accelerator rests on rails with separate carts for the high-voltage generator, PFL, and vacuum system. This also permits rapid access to critical accelerator elements. Quick-release hold-down clamps were used to attach the accelerator's endplate to the diode chamber allowing easy access to the accelerator's electrodes. While all of these features are of a purely practical nature, they contribute significantly to the value of the accelerator as a research tool.

CHAPTER 3

ELECTRON ACCELERATION

When high electric fields are applied to a conductor, electrons may be spontaneously emitted from their surface. This is referred to as cold field emission , as opposed to thermonic emission from heated cathodes. High-voltage, high-current electron accelerators almost universally use cold-field emission cathodes as does Transbeam. Two examples of diodes used for electron acceleration on Transbeam will be discussed. Also, some results from electron diagnostics are presented.

One typical electrode geometry used for electron acceleration on Transbeam is described as follows. The cathode is a 7.5 cm diameter planar carbon disk and the anode is a 0.6 mil titanium foil. The gap spacing is 15 mm. The diode voltage and current traces obtained using this diode were the ones previously described in Figure 1. Electrons are cold-field emitted from the carbon cathode and are accelerated toward the anode foil which is grounded. The anode foil thickness is small compared to the electron range and electrons penetrate it while losing little of their particle energy. For example, using stopping power calculations for 600 keV electrons, less than 2 percent of an electron's kinetic energy is lost in the 0.6 mil titanium anode foil. For some applications we require a smaller electron beam current than the full current delivered by a matched-load diode. Therefore, while still using a matched-load diode, we place a carbon disk with a 2 cm diameter aperture immediately downstream of the anode foil and extract a fraction of the total number of accelerated electrons. These electrons have been diagnosed with an emittance meter using the setup shown in Figure 3. An emittance meter allows measurement of electron beam radius and transverse temperature. The beam is separated into beamlets by the slits and are recorded on the radiachromic film detector. A microdensitometer scan of the radiachromic film is also shown in Figure 3. The width of each peak may be used to find the transverse temperature. The entire set of peaks may be analyzed to yield a beam profile from which the beam radius may be determined. Details of the method of analysis for emittance data may be found in Reference 7. For the data shown in Figure 3, the rms beam radius is 0.7 cm and the transverse temperature is 35 keV. A Rogowski coil was placed at the accelerator exit to determine beam current and shows a current typically with a peak value of 3-4 kA. Experiments which utilize this electron beam are attached to the accelerator's output. Therefore, these measurements on the electron beam as it emerges from the accelerator are important in determining initial beam conditions for any electron beam experiment.

Another electron beam diode that has been used is called a foilless diode. This diode has a 12 mm diameter stainless steel cathode. A stainless

steel disk with a 20 mm aperture on center is used as the anode. The anode-cathode gap was 5 mm. The electron energy spectrum of Transbeam using this diode has been measured with the magnetic spectrometer[8] shown in Figure 4. Electrons enter the spectrometer through a collimator and are bent in a semicircular path by the magnetic field. The diameter of the semicircle depends on electron energy. Electrons striking the phosphor detector cause emission of light which is recorded with a camera set up at the open end of the spectrometer. Figure 5 shows a microdensitometer scan of the black and white film used to record the energy spectrum. The peak at 0 energy is due to plasma light which shines through the collimator. Other peaks are due to phoshpor light. The peak at 140 keV may be due to a small amplitude reflected voltage pulse. The broad peak which extends from 400 to 700 keV represents the electrons accelerated during the main voltage pulse. Note that electrons are accelerated both during the rise time and fall time of the diode voltage pulse, which accounts for the large energy spread. For this shot the capacitor bank charging voltage was ±20 kV.

CHAPTER 4

ION ACCELERATION

A transformer-driven accelerator is particularly amenable for changing between electron acceleration and ion acceleration modes. All that is required is a reversal the dc power supply leads and a reconfiguration of the diode electrodes. Ion acceleration with Transbeam was performed as follows. The anode (which is now attached to the center conductor of the PFL) is a 12 mm diameter stainless steel cylinder with a polyethylene disk inserted in its end. The cathode (which is now the electrode attached to the grounded outer conductor of the PFL) is a 2 mil tantulum foil with a 70 mil diameter aperture on center which permits expulsion of some of the accelerated ions from the accelerator. The anode-cathode gap was 5 mm. The PFL charging voltage is shown in Figure 6, where the initial voltage swing is negative and the output switch breaks down on the positive swing of the second half cycle. The diode voltage is also shown here. The ions are diagnosed with a charged-particle analyzer which uses parallel electric and magnetic fields. This type of analyzer is called a Thomson spectrometer and is diagrammed in Figure 7. The Thomson spectrometer separates ions into parabolas according to their mass/charge ratio. The "length" of a parabola is due to energy spread. (References 9 and 10 give detailed descriptions of the Thomson spectrometer.) Spectrometer results are shown in Figure 8 where H^+, C^+, C^{2+}, and C^{3+} ions are shown. C^{4+} ions were also observed but do not appear in the photograph because of their low intensity. The peak energy of ions (i.e., ions which are deflected the least by the parallel fields) is identified as: H^+/480 keV, C^+/1730 keV, C^{2+}/1730 keV, C^{3+}/1730 keV, C^{4+}/1730 keV. We believe that originally the following ion/maximum energy conditions existed for carbon ions: C^+/430 keV, C^{2+}/870 keV, C^{3+}/1300, C^{4+}/1730 keV. These energies represent acceleration of particles with charge Z through a potential of ϕ(= 430 kV), where particles are accelerated to energies of $Z\phi$. Later after acceleration has taken place, the multiply charged ions may capture electrons and transfer to lower charge state parabolas, resulting in identical peak energies for all four charge states of carbon. For comparison with the measured peak ion energies, the diode voltage for this shot has a mean value of approximately 500 kV. The capacitor bank charging voltage for this example was ±20 kV.

CHAPTER 5

CONCLUSION

The Transbeam accelerator which has been developed and constructed at NSWC has proven to be a useful accelerator for basic research applications. It has been operated both as an electron accelerator and an ion accelerator.

In most cases we have used a capacitor bank charging voltage of ±25 kV. The high-voltage generator was designed for a capacitor bank charging voltage of ±50 kV, and an output voltage of 3 MV. This would result in a diode voltage of 1.5 MV. However, the diode insulator is a flat slab of dielectric, with no voltage grading as is used in most accelerators. It is estimated that the hold-off voltage for this insulator is 1 MV, therefore we have routinely chosen to operate the accelerator conservatively at lower values. However, the accelerator has been operated with higher impedance diodes than discussed in this report and has resulted in beams of higher energy (greater than 1 MeV) and lower current.

Although the beam energy of Transbeam is rather low for an intense relativistic electron beam, beam current and pulse length are considered formidable. However, perhaps the most advantagous characteristics of Transbeam are its reliability, shot rate, and low cost of operation. All of these characteristics are either directly or indirectly due to its simple design and small physical size. There has been a minimum of accelerator downtime and, when failures have occurred, the repair time has been minimal. The level of reliability has allowed a larger shot rate than in most larger accelerators, and we have operated some weeks with over 200 shots per week. When preparatory work can be performed at a lower energy, Transbeam is ideal as a test bed for experiments at higher energy. When relevant research or diagnostic development can be performed at Transbeam's energy, its extraordinary shot rate is a major advantage.

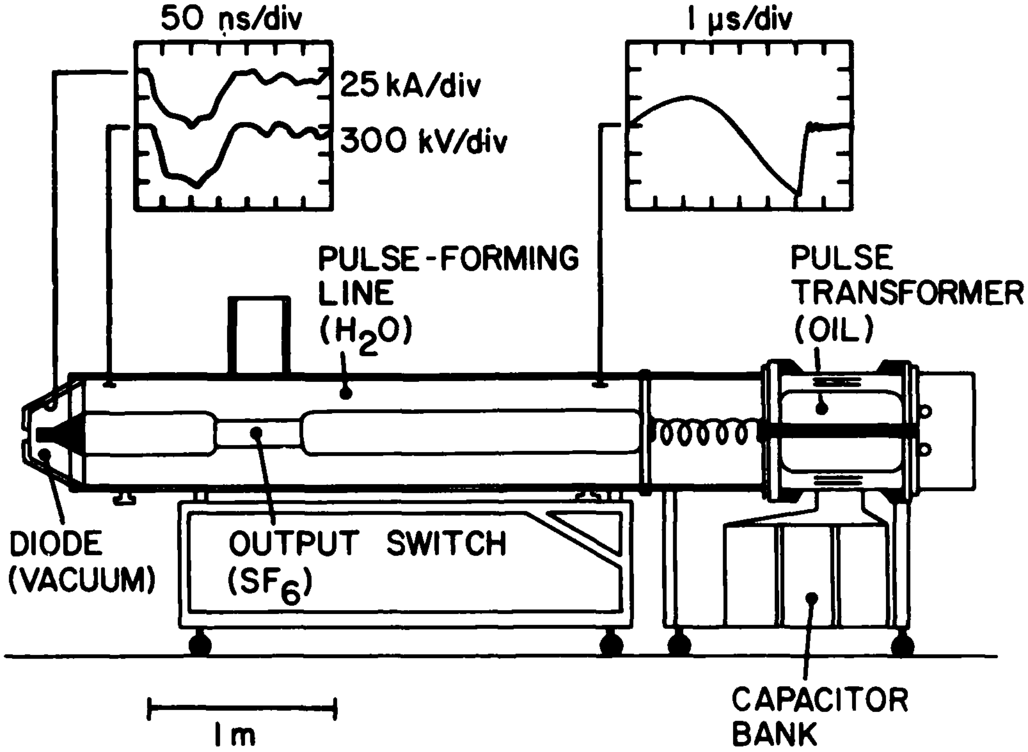


FIGURE 1. TRANSBEAM ACCELERATOR

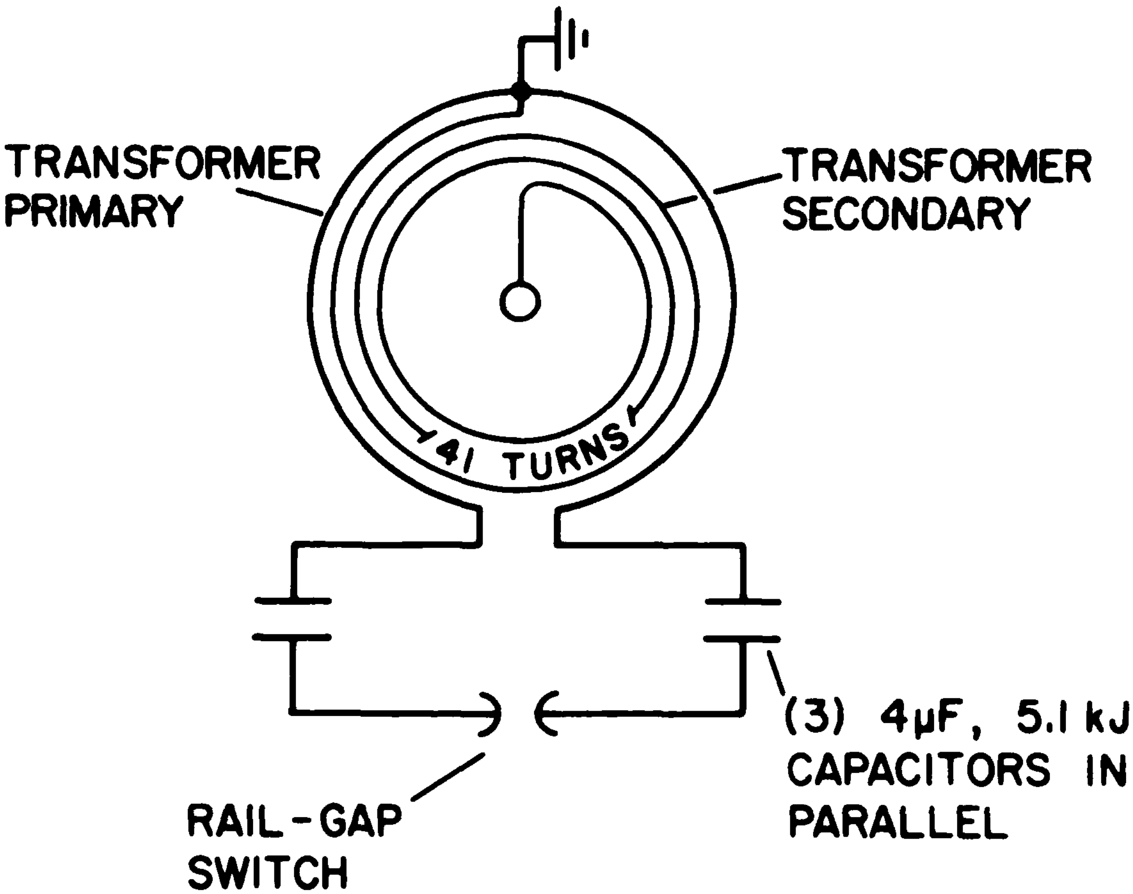


FIGURE 2. HIGH-VOLTAGE GENERATOR

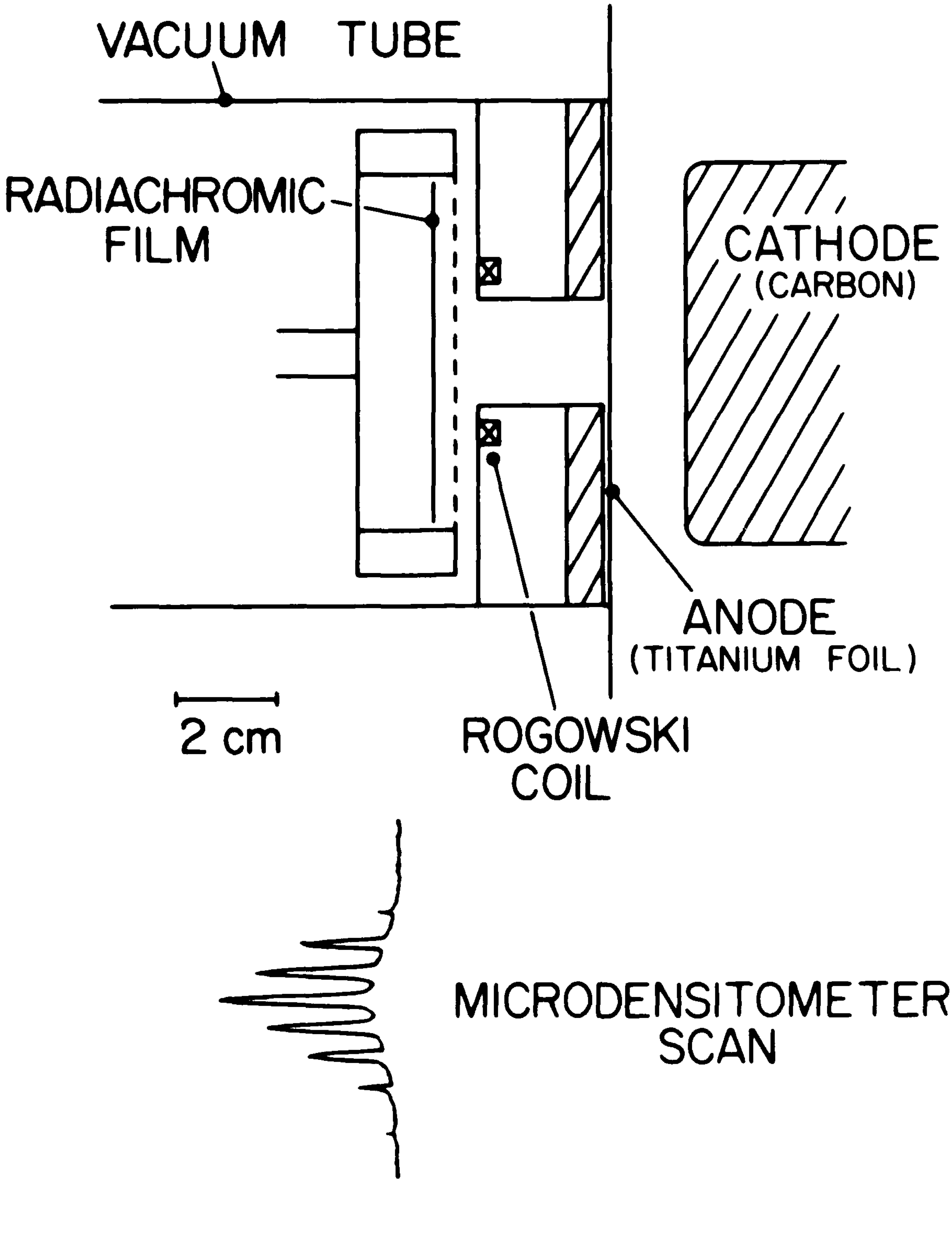


FIGURE 3. DIODE GEOMETRY AND EMITTANCE METER

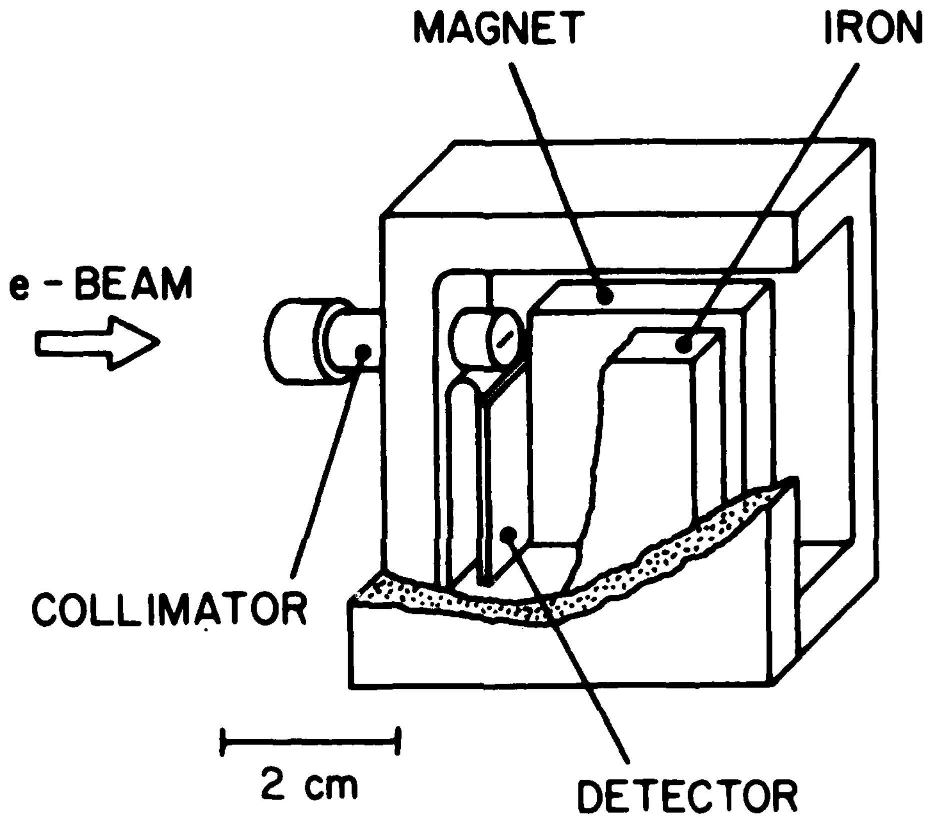


FIGURE 4. MAGNETIC SPECTROMETER

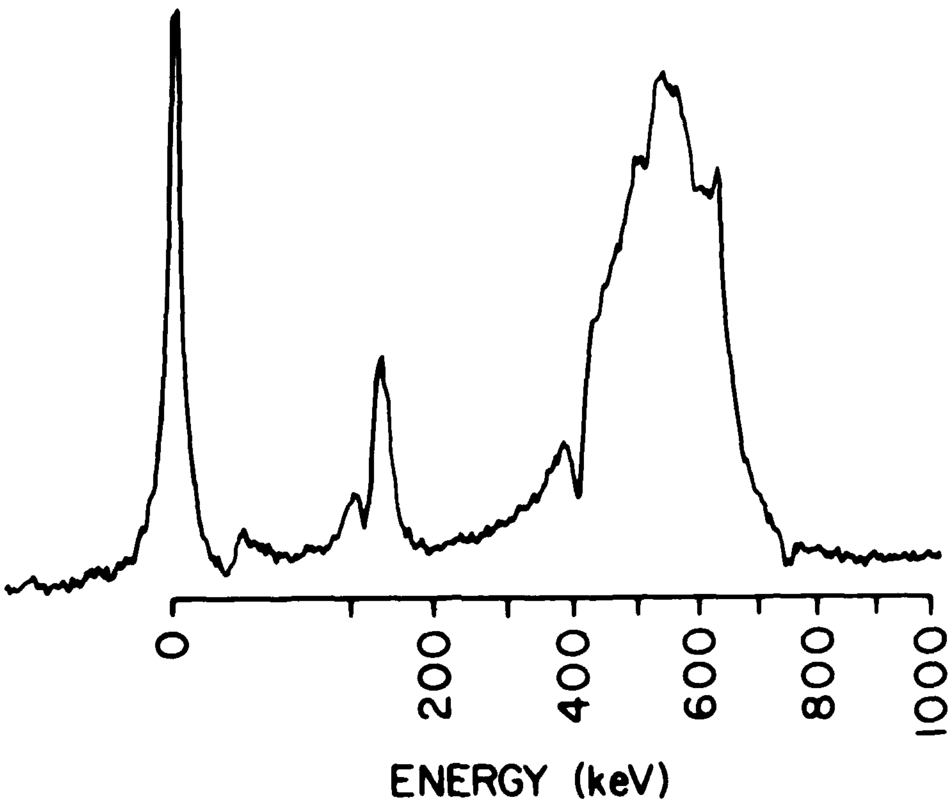
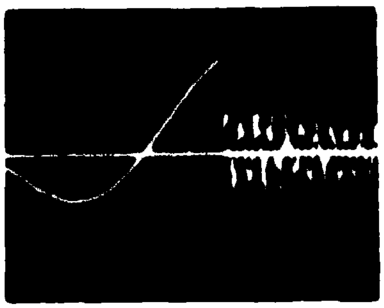
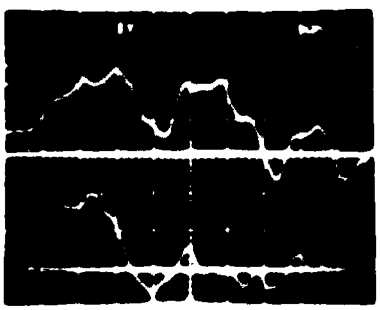


FIGURE 5. ENERGY SPECTRUM OF ELECTRONS



PFL CHARGING VOLTAGE

1 μs/DIV



DIODE CURRENT (24 kA/DIV)

DIODE VOLTAGE (300 kV/DIV)

50 ns/DIV

FIGURE 6. ION ACCELERATION WAVEFORMS

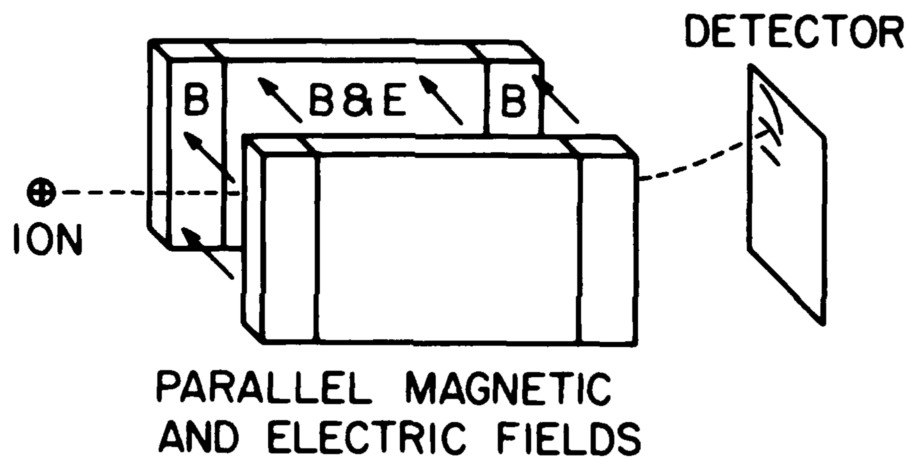


FIGURE 7. THOMSON SPECTROMETER

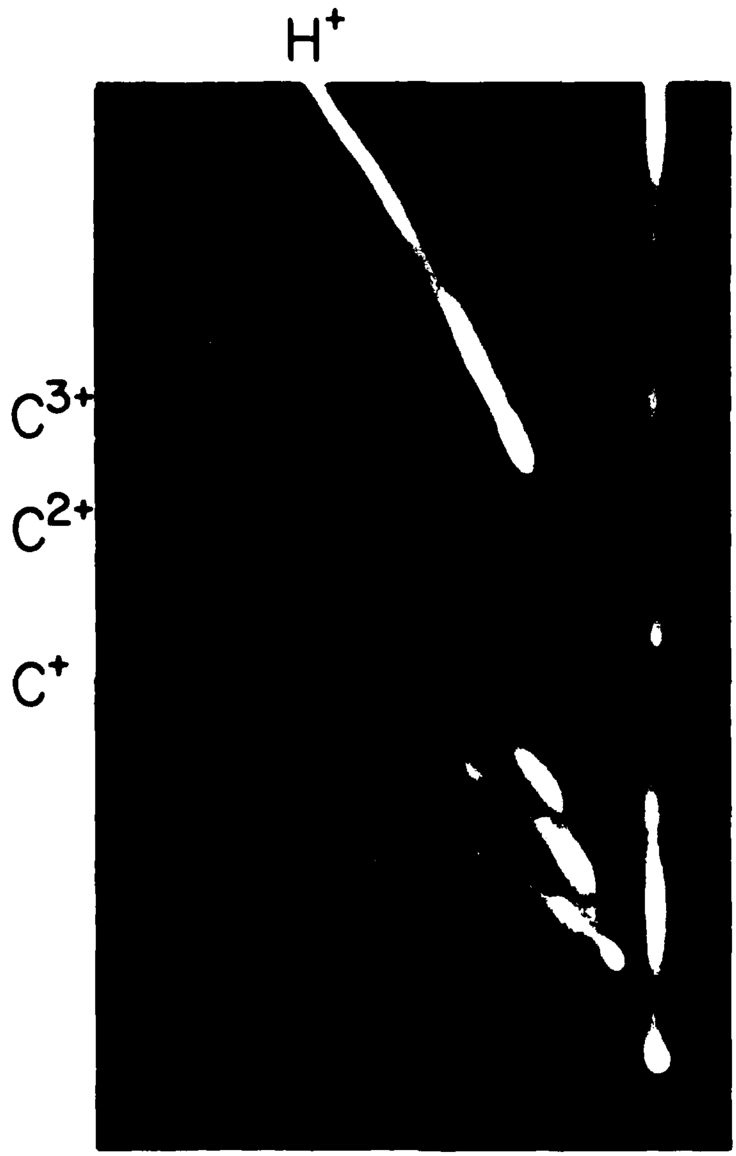


FIGURE 8. IONS RECORDED WITH THOMSON SPECTROMETER

TABLE 1. TRANSBEAM ACCELERATOR SPECIFICATIONS

Element	Description	
ENERGY STORAGE		
1. Number of capacitors	6	(counted)
2. Individual capacitor specs	4 μF, 50 kV, 5.1 kJ, 20 nH	
3. Effective total capacitance	6.15 μF	(calculated)
TRANSFORMER PRIMARY		
1. Turn radius	12.5 in	(31.8 cm)
2. Aluminum width	16 in	(40.6 cm)
3. Aluminum thickness	0.375 in	(0.95 cm)
4. Number turns	1	
5. Primary turn inductance	0.55 μH	(calculated)
TRANSFORMER SECONDARY		
1. Initial winding diameter	17.0 in	(43.2 cm)
2. Final winding diameter	23.0 in	(58.4 cm)
3. Mean radius	10.0 in	(25.4 cm)
4. Width of copper	12 in	(30.5 cm)
5. Width of mylar insulation	24 in	(61.0 cm)
6. Copper thickness	0.010 in	(0.025 cm)
7. Mylar thickness	0.005 in	(0.013 cm)
8. Paper thickness	0.0005 in	(0.0013 cm)
9. Total turn thickness (1 copper + 11 mylar + 1 paper)	0.0655 in	(0.1664 cm)
10. Number turns	41	
11. Total winding thickness	3 in	(7.62 cm)
12. Total length of winding	211 ft	
13. Secondary turn inductance	480 μH	(measured)
TUNING INDUCTOR SECTION		
1. Length	22.5 in	(57.2 cm)
2. Tuning inductor diameter	8.625 in	(21.9 cm)
3. Tuning inductor turns	31	(1.5/in)
4. Tuning inductor wire diameter (#10 AWG)	0.102 in	(2.6 mm)
5. Inductance	80 μH	
PULSE FORMING LINE		
1. Outer diameter	23.5 in	(59.7 cm)
2. Inner diameter	8.625 in	(21.9 cm)
3. Length	60 in	(1.52 m)
4. Impedance	6.8 Ω	(calculated)
5. Capacitance	6.6 nF	(calculated)
6. Inductance	300 nH	(calculated)
ISOLATION SECTION		
1. Length	41.25 in	(1.05 m)
2. Capacitance	4.6 nF	(calculated)
	20 nF	(measured)
3. Inductance	216 nH	(calculated)

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